High Energy Phenomena in Supergiant X-ray Binaries

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High Energy Phenomena in Supergiant X-ray Binaries

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Abstract. The INTEGRAL satellite has revealed a major population of supergiant High Mass X-ray Binaries in our Galaxy, revolutionizing our understanding of binary systems and their evolution. This population, constituted of a compact object orbiting around a massive and luminous supergiant star, exhibits unusual properties, either being extremely absorbed, or showing very short and intense flares. An intensive set of multi-wavelength observations has led us to reveal their nature, and to show that these systems are wind-fed accretors, closely related to massive star-forming regions. In this paper I describe the characteristics of these sources, showing that this newly revealed population is linked to the evolution of gamma-ray emitting massive stars with a compact companion.

1. The γ-ray sky seen by the *INTEGRAL* satellite

The *INTEGRAL* observatory is an ESA satellite launched on 17 October 2002 by a PROTON rocket on an excentric orbit. It is hosting 4 instruments: 2 γ-ray coded-mask telescopes –the imager IBIS and the spectro-imager SPI, observing in the range 10 keV-10 MeV, with a resolution of $12'$ and a field-of-view of $19°$– a coded-mask telescope JEM-X (3-100 keV), and an optical telescope (OMC).

The γ-ray sky seen by *INTEGRAL* is very rich, since 499 sources have been detected by *INTEGRAL*, reported in the 3^{rd} IBIS/ISGRI soft γ-ray catalogue, spanning 3.5 years of observations in the 20-100 keV domain (Bird et al. 2007). 214 sources were discovered by *INTEGRAL*, while the remaining 285 were already known. Among these sources, there are 147 XRBs (representing 29% of the whole sample of sources detected by *INTEGRAL*, called "IGRs" in the following), 163 AGNs (33%), 27 CVs (5%), and 20 sources of other type (4%): 12 SNRs, 2 globular clusters, 2 SGRs and 1 GRB. 129 objects still remain unidentified (26%). XRBs are separated in 82 LMXBs and 78 HMXBs (each category represents 16% of IGRs). Among the HMXBs, there are 24 BeXBs and 19 sgXBs (representing respectively 31% and 24% of HMXBs).

It is interesting to follow the evolution of the ratio between BeXBs and sgXBs. During the pre-*INTEGRAL* era, HMXBs were mostly BeXBs systems. For instance, in the catalogue of 130 HMXBs by Liu et al. (2000), there were 54 BeXBs and 7 sgXBs (respectively 42% and 5% of the total number of HMXBs). Then, the situation changed with the first HMXBs identified by *INTEGRAL*: in the catalogue of 114 HMXBs (+128 in Magellanic Clouds) of Liu et al. (2006), there were 60% of BeXBs and 32% of sgXBs firmly identified. Therefore, while the ratio of BeXBs/HMXBs increased by a factor of 1.5 only, the one of sgXBs/HMXBs increased by a factor of 6.

2. Let the *INTEGRAL* show go on!

The ISGRI detector on the IBIS imager has performed a detailed survey of the Galactic plane, discovering many new high energy celestial objects, most of which reported in Bird et al. (2007)[1]. The most important result of *INTEGRAL* to date is the discovery of many new high energy sources – concentrated in the Galactic plane, mainly towards tangential directions of Galactic arms, rich in star forming regions, – exhibiting common characteristics which previously had rarely been seen (see e.g. Chaty & Filliatre 2005). Many of them are HMXBs hosting a NS orbiting around an OB companion, in most cases a supergiant star. Nearly all the *INTEGRAL* HMXBs for which both spin and orbital periods have been measured are located in the upper part of the Corbet diagramme (Corbet 1986). They are wind accretors, typical of supergiant HMXBs, and X-ray pulsars exhibiting longer pulsation periods and higher absorption (by a factor ~ 4) as compared to the average of previously known HMXBs (Bodaghee et al. 2007). They divide into two classes: some are very obscured, exhibiting a huge intrinsic and local extinction, –the most extreme example being the highly absorbed source IGR J16318-4848 (Filliatre & Chaty 2004)–, and the others are HMXBs hosting a supergiant star and exhibiting fast and transient outbursts – an unusual characteristic among HMXBs. These are therefore called Supergiant Fast X-ray Transients (SFXTs, Negueruela et al. 2006), with IGR J17544-2619 being their archetype (Pellizza et al. 2006).

2.1. Multi-wavelength observations of *INTEGRAL* sources

To better characterise this population, Chaty et al. (2008) and Rahoui et al. (2008) studied a sample of 21 IGRs belonging to both classes described above. Sources of this sample are X-ray pulsars, with high $P_{\rm spin}$ from 139 to 5880 s and P_{orb} ranging from 4 to 14 days. They are therefore wind accreting supergiant HMXBs, according to the Corbet diagramme. The multiwavelength observations were performed from 2004 to 2008 at the European Southern Observatory (ESO), using Target of Opportunity (ToO) and Visitor modes, in 3 domains: optical (400 – 800 nm) with EMMI, NIR (1 – 2.5 μm) with SOFI, both instruments at the focus of the 3.5m New Technology Telescope (NTT) at La Silla, and mid-infrared (MIR, 5 – 20 μm) with the VISIR instrument on Melipal, the 8m Unit Telescope 3 (UT3) of the Very Large Telescope (VLT) at Paranal (Chile). They also used data from the GLIMPSE survey of *Spitzer*. With these observations they performed accurate astrometry, identification, photometry and spectroscopy on this sample of IGRs, aiming at identifying their counterparts and the nature of the companion star, deriving their distance, and finally characterising the presence and temperature of their circumstellar medium, by fitting their spectral energy distribution (SED).

The main results of this study are that 15 of these IGRs are identified as HMXBs, and among them 12 HMXBs contain massive and luminous early-type companion stars. By combining optical, NIR and MIR photometry, and fitting their SEDs, Rahoui et al. (2008) showed that (i) most of these sources exhibit an intrinsic absorption and (ii) three of them exhibit a MIR excess, which they suggest to be due to the presence of a cocoon of dust and/or cold gas enshrouding the whole binary system, with a temperature of $T_d \sim 1000$ K, extending on a radius of $R_d \sim 10\, R_\star$ (see Chaty & Rahoui 2006).

[1]See an updated list at *http://irfu.cea.fr/Sap/IGR-Sources/*

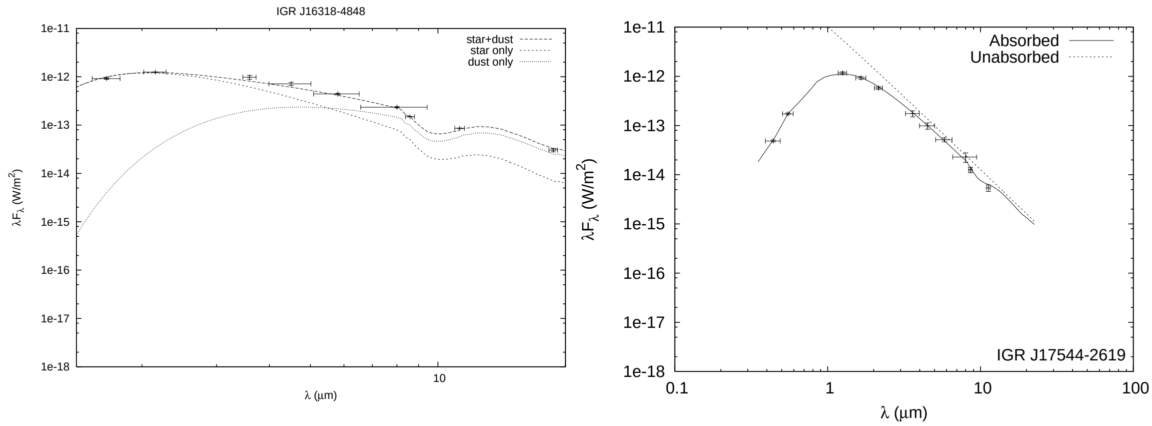

Figure 1. Optical to MIR SEDs of IGR J16318-4848 (left) and IGR J17544-2619 (right), including data from ESO/NTT, VISIR on VLT/UT3 and *Spitzer* (Rahoui et al. 2008). IGR J16318-4848 exhibits a MIR excess, interpreted as the signature of a strong stellar outflow coming from the sgB[e] companion star (Filliatre & Chaty 2004). On the other hand, IGR J17544-2619 is well fitted with only a stellar component corresponding to the O9Ib companion star spectral type (Pellizza et al. 2006).

2.2. Supergiant Fast X-ray Transients

General characteristics SFXTs constitute a new class of $\sim$ 12 sources identified among the recently discovered IGRs. They are HMXBs hosting NS orbiting around sgOB companion stars, exhibiting peculiar characteristics compared to “classical” HMXBs: rapid outbursts lasting only for hours, faint quiescent emission, and high energy spectra requiring a BH or NS accretor. The flares rise in tens of minutes, last for $\sim$ 1 hour, their frequency is $\sim$ 7 days, and their luminosity $L_x \sim 10^{36}$ erg s^{-1} at the outburst peak.

IGR J17544-2619, archetype of SFXTs This bright recurrent transient X-ray source was discovered by *INTEGRAL* on 17 September 2003 (Sunyaev et al. 2003). *XMM-Newton* observations showed that it exhibits a very hard X-ray spectrum, and a relatively low intrinsic absorption ($N_{\rm H} \sim 2 \times 10^{22}$ cm^{-2}, González-Riestra et al. 2004). Its bursts last for hours, and inbetween bursts it exhibits long quiescent periods, which can reach more than 70 days. The X-ray behaviour is complex on long, mean and short-term timescales: rapid flares are detected by *INTEGRAL* on all these timescales, on pointed and 200s binned lightcurve (Zurita Heras & Chaty in prep.). The compact object is probably a NS (in’t Zand 2005). Pellizza et al. (2006) managed to get optical/NIR ToO observations only one day after the discovery of this source. They identified a likely counterpart inside the *XMM-Newton* error circle, confirmed by an accurate localization from *Chandra*. Spectroscopy showed that the companion star was a blue supergiant of spectral type O9Ib, with a mass of $25 - 28\ M_\odot$, a temperature of $T \sim 31000$ K, and a stellar wind velocity of 265 ± 20 km s^{-1} (which is faint for O stars): the system is therefore an HMXB (Pellizza et al. 2006). Rahoui et al. (2008) combined optical, NIR and MIR observations and showed that they could accurately fit the observations with a model of an O9Ib star, with a temperature $T_\star \sim 31000$ K and a radius $R_\star = 21.9\ R_\odot$. They derived an absorption $A_v = 6.1$ magnitudes and a distance D = 3.6 kpc. Therefore the source does not exhibit any MIR excess, it is well fitted by a unique stellar component (see Figure 1, right panel, Rahoui et al. 2008).

Classification of SFXTs We can divide the SFXTs in two groups, according to the duration and frequency of their outbursts, and their $\frac{L_{\max}}{L_{\min}}$ ratio. The classical SFXTs exhibit a very low quiescence L_X and a high variability, while intermediate SFXTs exhibit a higher $< L_X >$, a lower $\frac{L_{\max}}{L_{\min}}$ and a smaller variability, with longer flares. SFXTs might appear like persistent sgXBs with $< L_X >$ below the canonical value of $\sim 10^{36}$ erg s^{-1}, and flares superimposed. But there might be some observational bias in these general characteristics, therefore the distinction between SFXTs and sgXBs is not well defined yet. While the typical hard X-ray variability factor (the ratio between deep quiescence and outburst flux) is less than 20 in classical/absorbed systems, it is higher than 100 in SFXTs (some sources can exhibit flares in a few minutes, like for instance XTE J1739-302 & IGR J17544-2619). The intermediate SFXTs exhibit smaller variability factors.

SFXT behaviour: clumpy wind accretion?

Such sharp rises exhibited by SFXTs are incompatible with the orbital motion of a compact object through a smooth medium (Negueruela et al. 2006, Smith et al. 2006, Sguera et al. 2005). Instead, flares must be created by the interaction of the accreting compact object with the dense clumpy stellar wind (representing a large fraction of stellar $\frac{dM}{dt}$). In this case, the flare frequency depends on the system geometry, and the quiescent emission is due to accretion onto the compact object of diluted inter-clump medium, explaining the very low quiescence level in classical SFXTs.

Macro-clumping scenario

Each SFXT outburst is due to the accretion of a single clump, assuming that the X-ray lightcurve is a direct tracer of the wind density distribution. The typical parameters in this scenario are: a compact object with large orbital radius: 10 $R_\star$, a clump size of a few tenths of $R_\star$, a clump mass of $10^{22-23} g$ (for $N_{\rm H} = 10^{22-23}$ cm^{-2}), a mass loss rate of $10^{-(5-6)}$ $M_\odot/yr$, a clump separation of order $R_\star$ at the orbital radius, and a volume filling factor: 0.02$-$ >0.1. The flare to quiescent count rate ratio is directly related to the $\frac{clump}{inter-clump}$ density ratio, which ranges between 15-50 for intermediate SFXTs, and 10^{2-4} for "classical" SFXTs. A very high degree of porosity (macroclumping) is required to reproduce the observed outburst frequency in SFXTs, in good agreement with UV line profiles and line-driven instabilities at large radii (Oskinova et al. 2007; Runacres & Owocki 2005; Walter & Zurita Heras 2007).

Difference sgXB/SFXT

To explain the emission of sgXB/SFXT, Negueruela et al. (2008) and Walter & Zurita Heras (2007) invoke the existence of two zones around the supergiant star, of high and low clump density respectively. This would naturally explain the smooth transition between sgXBs and SFXTs, and the existence of intermediate systems; the main difference between classical sgXBs and SFXTs being in this scenario the NS orbital radius. Indeed, a basic model of porous wind predicts a substantial change in the properties of the wind "seen by the NS" at a distance $r \sim 2\,R_\star$ (Negueruela et al. 2008), where we stop seeing persistent X-ray sources. There are 2-regimes: either the NS sees a large number of clumps, because it is embedded in a quasi-continuous wind; or the number density of clumps is so small that the NS is effectively orbiting in an empty space.

The observed division between sgXBs (persistent sgXBs and SFXTs) is therefore naturally explained by simple geometrical differences in the orbital configurations:

1. The obscured sgXBs (persistent and luminous systems) would have short and circular orbits lying inside the zone of stellar wind high clump density ($R_{orb} \sim 2\, R_\star$).

2. The intermediate SFXTs would have short orbits, circular or eccentric, and possible periodic outbursts, the NS being inside the narrow transition zone.

3. The classical SFXTs would have larger and eccentric orbital radius, the NS orbiting outside the high density zone.

<u>IGR J18483-0311: an intermediate SFXT?</u>

X-ray properties of this system were suggesting an SFXT (Sguera et al. 2007), exhibiting however an unusual behaviour: its outbursts last for a few days (to compare to hours for classical SFXTs), and the ratio $L_{max}/L_{min} \sim 10^3$ (its quiescence is therefore at a higher level than the ratio $\sim 10^4$ for classical SFXTs). Moreover, its orbital period P_{orb}=18.5d is low compared to classical SFXTs (with large/eccentric orbits). Finally, its orbital and spin periods ($P_{\rm spin}$=21.05s) located it ambiguously inbetween Be and sgXBs in the Corbet Diagramme. Rahoui & Chaty (2008) identified the companion star of this system as a B0.5Ia supergiant, unambiguously showing that this system is an SFXT. Furthermore, they suggest that this system could be the first firmly identified intermediate SFXT, characterised by short, eccentric orbit (with an eccentricity e between 0.4 and 0.6), and long outbursts... An ”intermediate” SFXT nature would explain the unusual characteristics of this source among ”classical” SFXTs.

2.3. Obscured HMXBs

IGR J16318-4848, an extreme case IGR J16318-4848 was the first source discovered by IBIS/ISGRI on *INTEGRAL* on 29 January 2003 (Courvoisier et al. 2003), with a 2′ uncertainty. *XMM-Newton* observations revealed a comptonised spectrum exhibiting an unusually high level of absorption: $N_{\rm H} \sim 1.84 \times 10^{24}$ cm^{-2} (Matt & Guainazzi 2003). The accurate localisation by *XMM-Newton* allowed Filliatre & Chaty (2004) to rapidly trigger ToO photometric and spectroscopic observations in optical/NIR, leading to the confirmation of the optical counterpart (Walter et al. 2003) and to the discovery of the NIR one (Filliatre & Chaty 2004). The extremely bright NIR source (B$>$ 25.4 ± 1; I = 16.05 ± 0.54, J = 10.33 ± 0.14; H = 8.33 ± 0.10 and Ks = 7.20 ± 0.05 magnitudes) exhibits an unusually strong intrinsic absorption in the optical (A_v = 17.4 magnitudes), 100 times stronger than the interstellar absorption along the line of sight (A_v = 11.4 magnitudes), but still 100 times lower than the absorption in X-rays. This led Filliatre & Chaty (2004) to suggest that the material absorbing in X-rays was concentrated around the compact object, while the material absorbing in optical/NIR was enshrouding the whole system. The NIR spectroscopy in the $0.95-2.5\,\mu$m domain allowed them to identify the nature of the companion star, by revealing an unusual spectrum, with many strong emission lines:

- H, HeI (P-Cyg) lines, characteristic of dense/ionised wind at v = 400 km/s,
- HeII lines: the signature of a highly excited region,
- [FeII]: reminiscent of shock heated matter,
- FeII: emanating from media of densities $> 10^5 - 10^6$ cm^{-3},
- NaI: coming from cold/dense regions.

All these lines originate from a highly complex, stratified circumstellar environment of various densities and temperatures, suggesting the presence of an envelope and strong stellar outflow responsible for the absorption. Only luminous early-type stars such as sgB[e] show such extreme environments, and Filliatre & Chaty (2004) concluded that IGR J16318-4848 was an unusual HMXB hosting a sgB[e] with characteristic luminosity of $10^6\,L_\odot$ and mass of $30\,M_\odot$, located at a distance between 1 and 6 kpc (see also Chaty & Filliatre 2005). This source would therefore be the second HMXB hosting a sgB[e] star, after CI Cam (see Clark et al. 1999).

The question of this huge absorption was still pending, and only MIR observations would allow to solve this question, and understand its origin. By combining optical, NIR and MIR observations, and fitting these observations with a model of sgB[e] companion star, Rahoui et al. (2008) showed that IGR J16318-4848 was exhibiting a MIR excess (see Figure 1, left panel), that they interpreted as due to the strong stellar outflow emanating from the sgB[e] companion star. They found that the companion star had a temperature of $T_\star = 22200\,$K and radius $R_\star = 20.4\,R_\odot = 0.1\,$a.u., consistent with a supergiant star, and an extra component of temperature T = 1100 K and radius R = $11.9\,R_\star = 1\,$a.u., with $A_v = 17.6$ magnitudes. Recent MIR spectroscopic observations with VISIR at the VLT showed that the source was exhibiting strong emission lines of H, He, Ne, PAH, Si, proving that the extra absorbing component was made of dust and cold gas.

By taking a typical orbital period of 10 days and a mass of the companion star of $20\,M_\odot$, we obtain an orbital separation of $50\,R_\odot$, smaller than the extension of the extra component of dust/gas ($= 240\,R_\odot$), suggesting that this dense and absorbing circumstellar material envelope enshrouds the whole binary system, like a cocoon (see Figure 2, left panel). We point out that this source exhibits such extreme characteristics that it might not be fully representative of the other obscured sources.

2.4. The Grand Unification: different geometries, different scenarios

In view of the results described above, there seems to be a continuous trend, from classical and/or absorbed sgHMBs, to classical SFXTs. We outline in the following this trend.

1. In "classical" sgXBs, the NS is orbiting at a few stellar radii only from the star. The absorbed (or obscured) sgXBs (like IGR J16318-4848) are classical sgXBs hosting NS constantly orbiting inside a cocoon made of dust and/or cold gas, probably created by the companion star itself. These systems therefore exhibit a persistent X-ray emission. The cocoon, with an extension of $\sim 10\,R_\star = 1\,$a.u., is enshrouding the whole binary system. The NS has a small and circular orbit (see Figure 2, left panel).

2. In "Intermediate" SFXT systems (such as IGR J18483-0311), the NS orbits on a small and circular/excentric orbit, and it is only when the NS is close enough to the supergiant star that accretion takes place, and that X-ray emission arises.

3. In "classical" SFXTs (such as IGR J17544-2619), the NS orbits on a large and excentric orbit around the supergiant star, and exhibits some recurrent and short transient X-ray flares, while it comes close to the star, and accretes from clumps of matter coming from the wind of the supergiant. Because it is passing through more diluted medium, the $\frac{Lmax}{Lmin}$ ratio is higher for "classical" SFXTs than for "intermediate" SFXTs (see Figure 2, right panel).

Although this scenario seems to describe quite well the characteristics currently seen in sgXBs, we still need to identify the nature of many more sgXBs to confirm it, and in particular the orbital period and the dependance of the column density with the phase of the binary system.

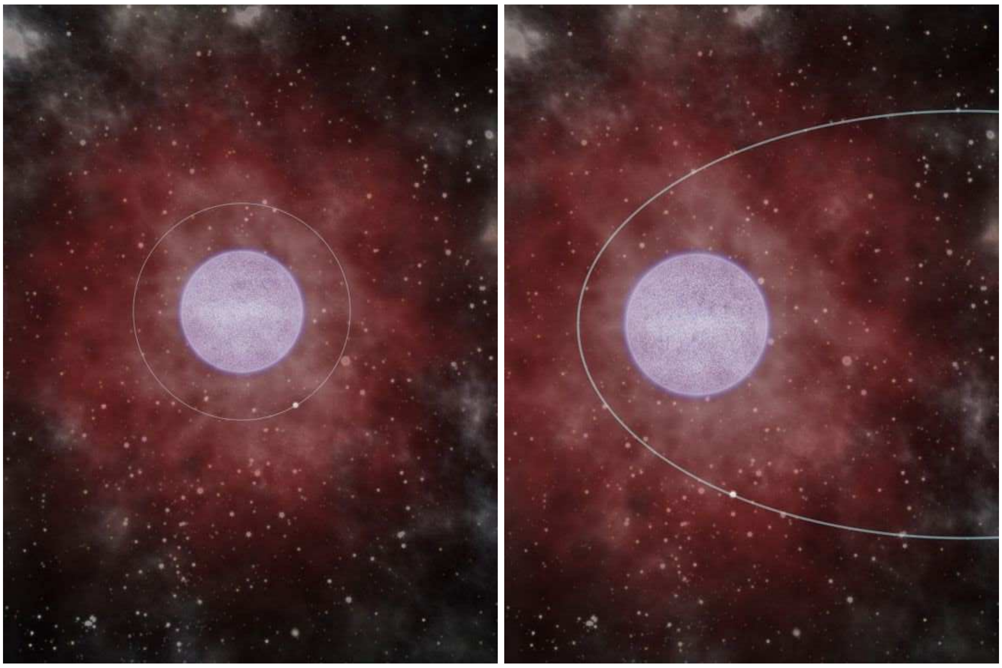

Figure 2. Scenarios illustrating two possible configurations of *INTEGRAL* sources: a NS orbiting a supergiant star on a circular orbit (left image); and on an eccentric orbit (right image), accreting from the clumpy stellar wind of the supergiant. The accretion of matter is persistent in the case of the obscured sources, as in the left image, where the compact object orbits inside the cocoon of dust enshrouding the whole system. On the other hand, the accretion is intermittent in the case of SFXTs, which might correspond to a compact object on an eccentric orbit, as in the right image. A 3D animation of these sources is available on the website:
http://www.aim.univ-paris7.fr/CHATY/Research/hidden.html

Population synthesis models These sources revealed by *INTEGRAL*, namely the supergiant HMXBs, will allow to better constrain and understand the formation and evolution of binary systems, by comparing them to numerical study of LMXB/HMXB population synthesis models. For instance, these new systems might represent a precursor stage of what is known as the ”Common envelope phase” in the evolution of LMXB/HMXB systems. Many parameters do influence the various evolutions of these systems: differences in size, orbital period, ages, accretion type, and stellar endpoints... Moreover, stellar and circumstellar properties also influence the evolution of high-energy binary systems, made of two massive components usually born in rich star forming regions. We still have to identify black holes orbiting around supergiant companion stars in wind-accreting HMXBs, however this is only feasible through observational methods involving detection of extremely faint radial velocity displacement due to the high mass of the companion star. Finally, these sources are also useful to look for massive stellar ”progenitors”, for instance giving birth to coalescence of compact objects, through NS/NS or NS/BH collisions. They would then become prime candidate for gravitational wave emitters, or even to short/hard γ-ray bursts.

3. Conclusions and perspectives...

The *INTEGRAL* satellite has tripled the total number of Galactic sgXBs, constituted of a NS orbiting around a supergiant star. Most of these new sources are slow and absorbed X-ray pulsars, exhibiting a large $N_{\rm H}$ and long $P_{\rm spin}$ (∼1ks). The influence of the local absorbing matter on periodic modulations is different for sgOB or BeXBs, segregated in different parts of $N_{\rm H}$-P_{orb} or $N_{\rm H}$-$P_{\rm spin}$. *INTEGRAL* revealed 2 new types of sources. First, the SFXTs, exhibiting short and strong X-ray flares, with a peak flux of 1 Crab during 1–100s, every $\sim$ 100 days. These flares can be explained by accretion through clumpy winds. Second, the obscured HMXBs are persistent X-ray sources composed of supergiant stellar companions exhibiting a strong intrinsic absorption and long $P_{\rm spin}$. The NS is deeply embedded in the dense stellar wind, forming a dust cocoon enshrouding the whole binary system.

These results show the existence in our Galaxy of a dominant population of a previously rare class of high-energy binary systems: supergiant HMXBs, some exhibiting a high intrinsic absorption (Chaty et al. 2008; Rahoui et al. 2008). Studying this population will provide a better understanding of the formation and evolution of short-living HMXBs. Furthermore, stellar population models now have to take these objects into account, to assess a realistic number of high-energy binary systems in our Galaxy.

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